

PROJECT ADMINISTRATION DATA SHEET

☒ ORIGINAL ☐ REVISION NO. _____

Project No. E-16-698 DATE 4/8/82
 Project Director: Dr. J. C. Wu School/Eng. Aerospace Eng.
 Sponsor: Air Force Office of Scientific Research, Bolling AFB, DC

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 Title: Studies in Nonlinear Unsteady Aerodynamics

ADMINISTRATIVE DATA

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Defense Priority Rating: NA

Security Classification: NA

RESTRICTIONS

See Attached AFOSR Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of \$500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT; See AFOSR Supplement and p. 1 of Grant Award Document.

COMMENTS:



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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEETDate 2/3/86Project No. E-16-698School XHX Aero. Engin.Includes Subproject No.(s) None IndicatedProject Director(s) J. C. Wu

GTRI / XHX

Sponsor AFOSR Bolling AFB, D.C.Title Studies in Non-Linear Unsteady AerodynamicsEffective Completion Date: 5/14/85(Performance) NONE

(Reports)

Grant/Contract Closeout Actions Remaining:

☒ None☐ Final Invoice or Final Fiscal Report☐ Closing Documents☐ Final Report of Inventions☐ Govt. Property Inventory & Related Certificate☐ Classified Material Certificate☐ Other _____Continues Project No. E-16-604Continued by Project No. E-19-655

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2. PROGRESS REPORT

2.1 Abstract

Progress has been made in applying a general viscous theory of aerodynamics and an integral-representation zonal procedure to three focal problems in unsteady aerodynamics. Computed as well as theoretical results have been obtained for an airfoil/vortex encounter problem, which involves unsteady flows over a rigid body, and the Weis-Fogh problem, which concerns flows induced by large amplitude unsteady motions of a non-rigid body. For each problem, fluid dynamic elements which dominate the aerodynamics of non-linear unsteady flows have been identified and their contributions to unsteady aerodynamic loads evaluated. The investigators are particularly gratified by results obtained for the Weis-Fogh problem. These results represent only a few initial steps in an overall program of study of unsteady aerodynamics of flexible lifting bodies underlying large amplitude motions. They demonstrated conclusively, however, that the establishment of a rational framework for the prediction and utilization of large unsteady aerodynamic forces is a realistic goal for the near future.

2.2 Six-Month Progress

Three focal problems in unsteady aerodynamics have been selected for theoretical and computational investigation under the present research program. These focal problems are: (1) Unsteady aerodynamic forces acting on an airfoil encountering a passing vortex, (2) Unsteady aerodynamic forces and power expenditures associated with the Weis-Fogh motion, and (3) Concepts of anchoring, or trapping, vortices near lifting bodies. These focal problems are all in the non-linear domain of unsteady aerodynamics. Each of these three problems represents an important facet of non-linear unsteady aerodynamics.

Considerable progress has been made during the first year of this program in applying a general viscous theory of aerodynamics (Reference 12) to problems of

non-linear unsteady aerodynamics involving rigid lifting bodies. Results of the first year's theoretical studies are described in Reference 13 which is made a part of the present proposal as an Appendix. In addition to the theoretical studies, computational efforts were carried out to further develop and refine a zonal procedure (Reference 15) for computing unsteady flows.

During the current program year, work continued in theoretical and computational studies of the three focal problems stated above. Considerable emphasis was placed on the Weis-Fogh problem which involves a non-rigid lifting body. Studies of the Weis-Fogh problem may be viewed as a precursor to a comprehensive study of unsteady aerodynamics involving flexible lifting bodies. Progress made during the first six months of the current program year is reviewed below.

(1). Airfoil/Vortex Encounter

In studies reported in Reference 13, vorticity in the unsteady boundary layer surrounding the airfoil and in the wake trailing the airfoil are approximated by discrete vortex sheets. The passing vortex is approximated by a vortex filament. The viscous diffusion of the passing vortex and the wake vortices is neglected. Results for the unsteady lift acting on the airfoil obtained using the general viscous theory of aerodynamics are found to be in agreement with the results obtained by previous investigators using the circulation theory (e.g., Reference 16). These results indicate that the airfoil/vortex encounter can result in large unsteady aerodynamic loads, particularly the lift acting on the airfoil. Unsteady drag, not analyzed by previous investigators, is evaluated in the present study. It is found that the unsteady drag can be negative, indicating a thrust force acting on the airfoil, during a part of the encounter period.

During the current program year, a parametric study of the unsteady aerodynamic loads resulting from the airfoil/vortex encounter for flows containing

no appreciable separated regions has been carried out. The parameters considered are the shape of the airfoil, the strength of the passing vortex, the distance of passing between the airfoil and the vortex, the angle of attack of the airfoil. In addition, flows that may contain massive separated regions are being examined through numerical solutions of the Navier-Stokes equations. Based on the results obtained during the first program year, it is anticipated that, with an airfoil not in stall, the passing vortex may induce massive flow separation. Conversely, with a stalled airfoil, the passing vortex may suppress the separation which exists before the encounter. The occurrence of encounter-induced separation on the airfoil has been verified in a preliminary computation utilizing an existing compressible Navier-Stokes airfoil code, modified to accept the presence of the passing vortex. Computed streamlines contours are shown in Figures 1 - 4 for a typical case where the passing vortex is initially located one-half chord below the airfoil. The computed solution shows substantial effects of flow separation on the unsteady aerodynamic loads. Additional efforts are in progress to prepare the zonal method (Reference 7) for future studies of the airfoil/vortex encounter problem involving massive separated regions.

(2) Weis-Fogh Motion

Weis-Fogh (Reference 16) suggested a mechanisms through which a wing in a wing-pair configuration acquires a circulation without shedding starting vortices from the trailing edge of the wing. Previous investigators (References 17 and 18) have presented theoretical results for the wing's circulation during the fling phase of the Weis-Fogh motion. The problems of unsteady lift, unsteady drag, and power expenditure associated with the Weis-Fogh motion have been studied in the current program year. These problems, to the knowledge of the present investigators, have not been studied by previous investigators. Results of these studies are of obvious

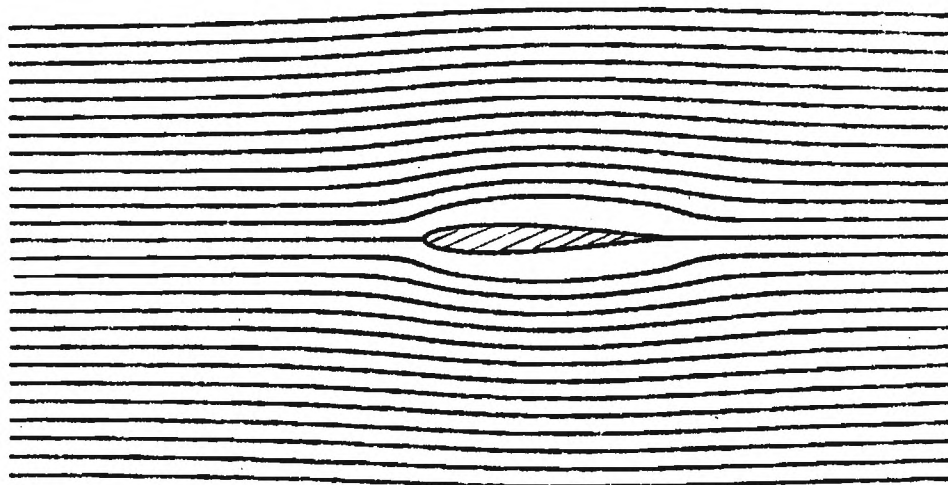


Figure 1. Symmetric flow field around a NACA 0012 airfoil. $Re = 5000$, $M_\infty = 0.2$ prior to the introduction of the vortex.

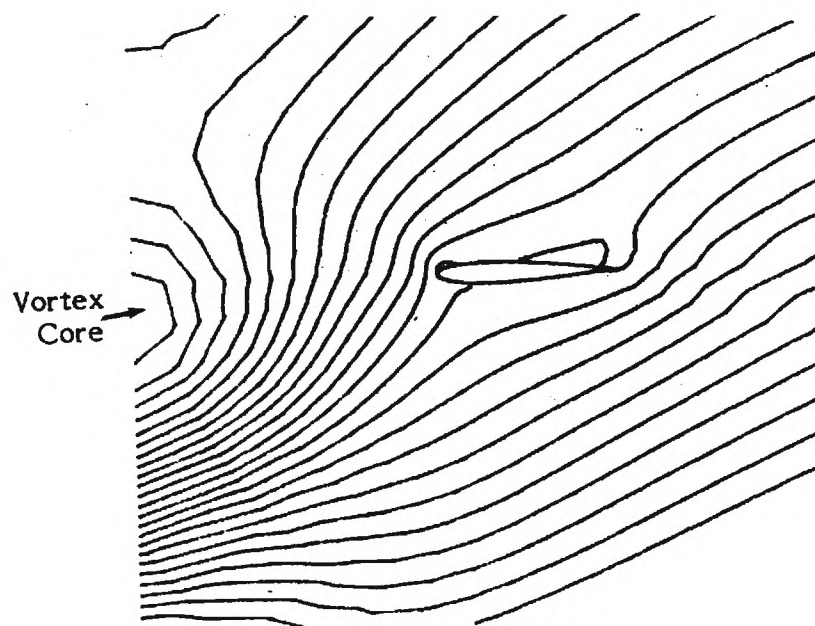


Figure 2. Streamline contours around a NACA 0012 airfoil. $Re = 5000$, $M_\infty = 0.2$, $t = 0.2$.

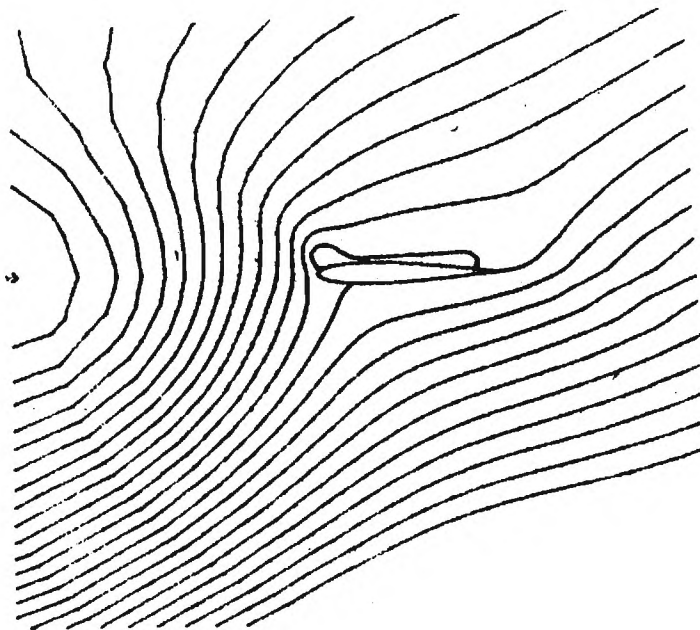


Figure 3. Streamline contours around a NACA 0012 airfoil. $Re = 5000$, $M_{\infty} = 0.2$, $t = 0.4$.

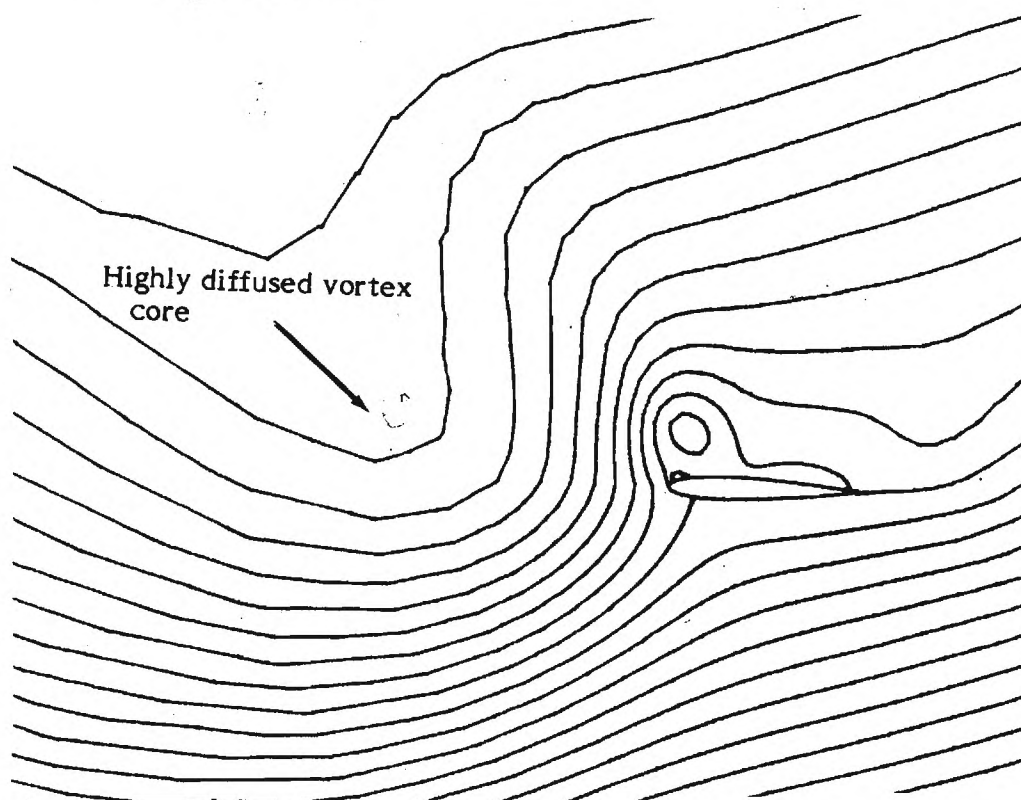


Figure 4. Streamline contours around a NACA 0012 airfoil. $Re = 5000$, $M_{\infty} = 0.2$, $t = 1.0$.

importance in the establishment of a comprehensive understanding of unsteady aerodynamics in the non-linear domain.

The ability of the general viscous theory of aerodynamics to identify and to separately evaluate the individual contributions of each of the vortical flow components present in an unsteady flow to the aerodynamic load is conclusively demonstrated by the present study of the Weis-Fogh problem. Closed form analytical expressions are obtained for the unsteady lift, the unsteady drag, and the power expenditure of the Weis-Fogh motion during the fling and the clap phases. In these analytical expressions, contributions of different vortical components of the flow are given individually. In the cases where the interaction of two flow components yields an additional contribution to the aerodynamic load, this interactive contribution is also expressed separately. For example, the lift L and the power expenditure P are expressed as

$$L = L_1 + L_2 \quad (3)$$

$$P = P_1 + P_2 + P_3 \quad (4)$$

In Eq. (3), L_1 represents the contribution to lift due to the wing's motion, without accounting for the vorticity shed from the leading edge of the wing. L_2 represents the contribution to lift due to the shed vorticity. There is no interactive contribution to lift. In Eq. (4), P_1 and P_2 represent the contributions due to, respectively, the wing's motion and the shed vorticity. There is an interactive contribution to the power expenditure, represented by P_3 in Eq. (4).

These individual contributions can be further expressed in component forms. For example, the lift L_1 can be written as

$$L_1 = \rho c^3 \dot{\Omega} f_{\ell 1} + \rho c^3 \Omega^2 g_{\ell 1} \quad (5)$$

where ρ is the density of the fluid, c is the chord length of the Weis-Fogh wing, Ω and $\dot{\Omega}$ are respectively the angular velocity and angular acceleration of the wing, $f_{\ell 1}$ and $g_{\ell 1}$ are functions of the wing pair's opening angle α . Equation (5) shows that the unsteady lift on the Weis-Fogh wing contains two effects, due respectively to the angular velocity and the angular acceleration of the wing. Analytical expressions for $f_{\ell 1}(\alpha)$ and $g_{\ell 1}(\alpha)$ are presented in Reference 14. In Figure 5, these two functions are shown graphically. In deriving these analytical expressions, the Weis-Fogh wing is assumed to be thin. If this assumption is relaxed, then an additional term appears on the right-hand side of Eq. (5). This term is of the form $\rho \dot{\Omega} A$, where A is the apparent mass of the wing cross-section. This apparent mass is easily determinable using the general viscous theory of aerodynamics (Reference 13).

The power expenditure P_1 can be expressed in two terms similar to Eq. (5). Analytical expressions for P_1 , P_2 , and L_2 are presented in Reference 14, included as an appendix of the proposal.

(3). Vortex Anchoring

A zonal procedure, developed by Wu and Gulcat (Reference 7) is being modified and refined for the study of the vortex anchoring concept. This zonal procedure treats the boundary layers separately from the detached recirculating and wake components of the flow. This procedure is highly efficient and highly accurate and is ideally suited for high Reynolds number flow computations.

2.3 Plans for Remaining Months

During the remaining months of the present program year, it is planned to continue the studies already in progress. The following tasks are expected to be carried out.

- a. The zonal procedure for computing viscous flows will be further refined.

This task is expected to continue beyond the end of the current program year. This

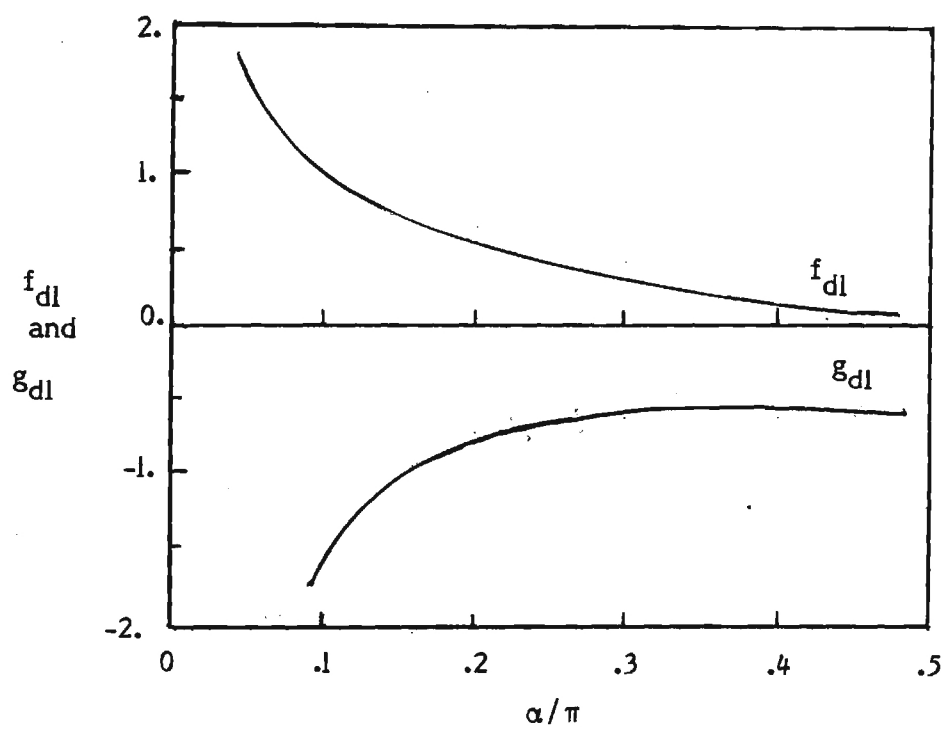


Figure 5. Weis-Fogh Drag Functions. $\frac{D_1}{\rho c^3} = \dot{\Omega} f_{dl} + \Omega^2 g_{dl}$

zonal procedure will be utilized subsequently in computing vortex/airfoil interactive flows as well as vortex anchoring flows involving massive separated regions.

b. The considerable amount of new information generated for the Weis-Fogh problem will be consolidated. Plans will be made to relax some of the simplifying assumptions utilized in the theoretical studies carried out thus far. As stated earlier, the Weis-Fogh problem involves the aerodynamics of a non-rigid lifting body. The study of the Weis-Fogh problem is a precursor of a more inclusive study of unsteady aerodynamics of flexible lifting bodies. A major emphasis of future efforts under the present program will be the establishment of a practical and reasonably general procedure for the study of unsteady aerodynamics involving large amplitude motion of flexible lifting bodies. Efforts during the remainder of the current program year will be motivated substantially by this emphasis.

c. Additional parametric studies of unsteady aerodynamic loads resulting from the interaction of the airfoil flow with a passing vortex will be carried out. In particular, the zonal Navier-Stokes solver will be prepared and utilized in these parametric studies dealing with flows that may contain separated regions.